Research Article | Vol. 26, No. 4 | 19 Feb 2018 | OPTICS EXPRESS 4075
Optics EXPRESS

Transparent effect on the gray scale perception of a transparent OLED display

Hyosun Kim,[1,*] Young-Jun Seo,[1] and Youngshin Kwak[2]

[1] *R&D Center, Samsung Display Co. Ltd., #1 Samsung-ro, Giheung-gu, Yongin 17113, South Korea*
[2] *Department of Human and systems Engineering, School of Design and Human Engineering, UNIST, Ulsan, South Korea*
[*] *hs0411.kim@samsung.com*

Abstract: Gray scale perception of transparent OLED displays was explored. The difference in luminance between transparent and non-transparent stimuli in the overall gray range was compared. The transparent effect appeared in gray scale perception. The range of the transparent effect was determined experimentally. To explore the practical application of this effect, we proposed a new tone-curve based on the transparent effect. In the preference experiment, participants indicated a higher preference score for the new tone-curve. This implied that the transparent effect is valid and applicable to real situations.

OCIS codes: (330.5020) Perception psychology; (330.5510) Psychophysics; (330.1720) Color vision.

References and links

1. H. J. Kwon, C. M. Yang, M. C. Kim, C. W. Kim, J. Y. Ahn, and P. R. Kim, (2016). "Modeling of Luminance Transition Curve of Transparent Plastics on Transparent OLED Displays," in *Electronic Imaging* (EI, 2016), pp. 1–4.
2. Z. Qin, Y. P. Huang, and H. P. D. Shieh, "Pixel Structure Evaluation Regarding See-through Image Quality for Transparent Displays: A Study Based on Diffraction Calculation and Full-Reference Image Quality Assessment," in *SID Symposium Digest of Technical Papers* (SID, 2017), pp. 615–618.
3. C. M. Yang, C. W. Kim, H. J. Kwon, M. C. Kim, J. Y. Ahn, and P. R. Kim, "Evaluation of Perceived See-through Level for Transparent OLED Displays," in *SID Symposium Digest of Technical Papers* (SID, 2017) pp. 1363–1366.
4. C. M. Yang, D. H. Lee, K. S. Park, Y. T. Kim, and C. W. Kim, "Comparison of Measures of Blurriness in Transparent Displays," in *Electronic Imaging* (EI, 2017), pp. 76–79.
5. B. H. Yu, J. W. Huh, J. Heo, and T.-H. Yoon, "Simultaneous control of haze and transmittance using a dye-doped cholesteric liquid crystal cell," Liq. Cryst. **42**(10), 1460–1464 (2015).
6. C. C. Li, H. Y. Tseng, H. C. Liao, H. M. Chen, T. Hsieh, S. A. Lin, H. C. Jau, Y. C. Wu, Y. L. Hsu, W. H. Hsu, and T. H. Lin, "Enhanced image quality of OLED transparent display by cholesteric liquid crystal back-panel," Opt. Express **25**(23), 29199–29206 (2017).
7. Y. Park, D. Kang, S. Kim, T. Han, J. Yoo, and M. Lim, "Simulation of Visual Quality for Transparent OLED Display," in *SID Symposium Digest of Technical Papers* (SID, 2013), pp. 156–159.
8. Y. Kwak, Y. S. Baek, and J. C. Kim, "Optimal tone curve characteristics of transparent display for preferred image reproduction," in *SID Symposium Digest of Technical papers* (SID, 2014), pp. 1123–1126.
9. Y. Kwak, H. Ha, S. Lee, H. Kim, Y. J. Seo, and B. Yang, "Optimal monitor gamma of transparent display," in *SID Symposium Digest of Technical papers* (SID, 2015), pp. 196–199.
10. H. Kim, Y. J. Seo, B. Yang, and H. Y. Chu, "Black perception in a transparent OLED display," Opt. Express **25**(4), 3954–3965 (2017).
11. S. Yamada, "Space brightness affected by a scenic view through a window," in *Proceedings of Association Internationale de la Couleur Midterm Meeting* (AIC, 2015), pp. 1211–1216.
12. F. A. Kingdom, "Lightness, brightness and transparency: A quarter century of new ideas, captivating demonstrations and unrelenting controversy," Vision Res. **51**(7), 652–673 (2011).
13. B. L. Anderson and J. Winawer, "Layered image representations and the computation of surface lightness," J. Vision **8**(7), 1–22 (2008).
14. M. Singh, "Lightness constancy through transparency: internal consistency in layered surface representations," Vision Res. **44**(15), 1827–1842 (2004).
15. M. Singh and B. L. Anderson, "Toward a perceptual theory of transparency," Psychol. Rev. **109**(3), 492–519 (2002).
16. C. S. Hwang, S. H. Park, and K. I. Cho, "Technical trends and prospects in transparent display," Electronics and telecommunications trends **25**(5), 20–32 (2010).
17. Telecommunications Technology Association (TTA) ICT Standardization Committee, "Viewing safety guideline for wearable content," Standard No. TTAK.KO-10.0860/R1 (2016).

#314206 https://doi.org/10.1364/OE.26.004075
Journal © 2018 Received 23 Nov 2017; revised 12 Jan 2018; accepted 30 Jan 2018; published 7 Feb 2018

Optics EXPRESS

1. Introduction

The biggest distinguishing feature of transparent displays, compared to normal non-transparent displays, is the ability to observe surroundings behind the panel. In order to emphasize this characteristic, there have been studies on how the images behind the display was perceived by humans [1–4]. However, the key function of a transparent display is, of course, to produce images in high fidelity. This, in turn, led to a few reports that actually proposed applying additional structures to partially block the exterior lights [5,6]. Regardless of these conflicting approaches to study transparent displays, it is necessary to start with a fundamental research on human perception of the images on a transparent display in ambient surround conditions, in order to improve the perceived image quality.

When perceiving an image on a transparent OLED display under an ambient surround condition, the total amount of luminance entering a person's eyes is the sum of the self-luminous light from the images and surround luminance from ambient light transmitted through the display. This can be expressed as the following equation:

$$Y_{eye} = Y_{display} + T \cdot Y_{lightings} \tag{1}$$

where T is the transmittance of a transparent display, $Y_{display}$ is the luminance of the self-luminous input image, $Y_{lightings}$ is the luminance of the surround lightings, and Y_{eye} is the total amount of luminance entering the person's eyes.

If we assume that the perceived brightness is the same as the luminance entering a person's eyes, regardless of whether a display is transparent or not, the brightness of an image on a transparent display can be obtained from Eq. (1). Suppose that the luminance of the self-luminous input image is 10 cd/m^2 and the luminance of transmitted surround lighting is 40 cd/m^2 on a transparent display. Then, a person will judge the brightness of the image on the transparent display the same as a stimulus with a luminance of 50 cd/m^2 on a non-transparent display. In previous research, authors made this assumption and calculated the luminance [7] or lightness (L*) curves [8,9] of images presented on a transparent display.

However, this assumption does not hold for black perception of a transparent display. In previous research [10], the brightness of the transmitted light through a transparent display did not match the value predicted by this assumption. When the luminance was similar for both a non-transparent and transparent patch, participants perceived the transparent patch as darker, termed the "transparent effect". Because a transparent patch also plays the role of a window, showing the background overlapping with a transparent display, transparency may affect the perception of brightness.

A similar phenomenon also occurs for perceiving space brightness [11]. Participants were asked to rate the brightness of two spaces: one with ceiling lights and another with light from a window. While the intensities of the room illuminance were same, the participants' perception of the brightness of the room for the window case was lower. Therefore, the brightness of light from the window did not match the value predicted by the assumption. Hence, a medium, such as a window, affects a person's judgment of brightness.

The results of previous studies [10,11] imply that brightness perception is affected by a medium when a person perceives light passed through the medium. It is necessary to quantify the influence of medium on brightness, but it is not easy to derive it from the results of the previous studies. In the study regarding black perception in a transparent display [10], the transparent effect was observed only at the brightness of gray 0. In the study of space brightness [11] perception, it was difficult to calculate the difference in brightness between the reference without the medium and the test stimuli with the medium, because the brightness was measured using subjective judgment. Participants rated the brightness of the test stimuli by comparison with the reference stimuli. Brightness of the reference stimuli was a set value of 100. Brightness of 100 is an arbitrary value. Therefore, the physical amount of light in the test room, corresponding to 100 lx with a brightness of 100, cannot be estimated.

Moreover, the range of luminance that is required for the appearance of the effect of the medium, as well as its magnitude, need to be determined. According to the study on the perception of space brightness [11], the effect of the medium did not appear in the overall range. It appeared in the room with 100 lx and 300 lx, and not for 1000 lx. Similarly, the transparent effect may also disappear above a certain intensity of light.

The purpose of this study was to observe the gray scale perception of a transparent OLED display and to determine the range of luminance in which the transparent effect appears. In addition, we suggested an optimal tone-curve for improving the image preference based on the range of the transparent effect. In Experiment 1, we compared the difference of luminance between transparent and non-transparent stimuli in the transparent display in the overall tone-range. From these results, the range of the transparent effect was determined. Based on the results of Experiment 1, we suggested a tone-curve, which was corrected within the range of the transparent effect. In Experiment 2, the subjective preference of the suggested tone-curve was measured. If the assumption of the transparent effect was correct, the preference of the tone-curve based on the transparent effect was higher.

2. Experiment 1: gray scale perception in a transparent OLED display

For exploring gray scale perception in a transparent display, we compared a transparent test stimulus with a non-transparent reference stimulus on a transparent OLED display to determine the range of the transparent effect.

2.1 Method

The experimental setup had a within-subject design. The independent variables were the surround luminance and correlated color temperature (CCT) of the surround lightings. There were four levels of surround luminance: ambient conditions 1, 2, 3, and 4 (Table 1). The four ambient surround conditions were 20~99% of the luminance of a display. While the brightness of the surround lightings was generally expressed in units of lx, we used the surround luminance (cd/m^2), because the amount of light that entered from exterior lightings to a transparent display was important in this study. We set the focus of the luminance meter to the screen of the transparent display and then measured the luminance at the focus after removing the transparent display. The three levels of CCT of the surround lightings were: 5500, 6500, and 13000 K. Due to limitations of the lighting booth for 13000 K, ambient 1 condition was excluded and ambient 2 condition had a lower luminance of 50 cd/m^2, compared with the other CCT conditions.

Table 1. Surround Luminance and Transmitted Lightings through the Transparent Display

Surround Luminance (cd/m^2)	Luminance of transmitted lightings (cd/m^2)		
	5500 K	6500 K	13000 K
Ambient 1 (450 cd/m^2)	125.9	121.6	-
Ambient 2 (350 cd/m^2)*	88.7	90.3	72.5
Ambient 3 (250 cd/m^2)	64.1	64.8	65.3
Ambient 4 (150 cd/m^2)	39.86	39.6	40.5

* 13000 K (300 cd/m^2): lower luminance of 50 cd/m^2 compared with the other CCTs.

The participants were given the task of adjusting the luminance of a test stimulus (transparent) to match the brightness of a reference patch (non-transparent). This method was advantageous to calculate the transparent effect by comparing directly the difference between transparent stimulus and non-transparent stimulus. The sizes of the reference and test stimuli covered a visual angle of 2° (viewing distance: 150 cm). The inter-stimulus distance was a visual angle of 20° so that the two patches had transparent backgrounds with a visual angle of 10° in Fig. 1.

Optics EXPRESS

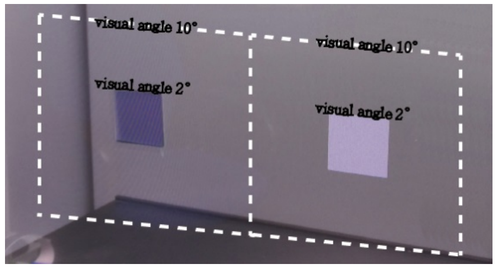

Fig. 1. Non-transparent and transparent reference stimuli, shown by the left and right rectangles, respectively, in the transparent display.

A reference stimulus was displayed on the opaque area of the transparent display. To produce the opaque stimulus, two linear polarized films were attached to the rear side of the display. If two films overlapped by 90°, light does not transmit theoretically, as shown in our previous study [10]. The reference stimulus had fifteen levels: 10–100 gray with a step size of 10 gray, and 120–200 gray with a step size of 20 gray. The luminance of the reference stimulus is shown in Table 2. We estimated that the differences in the luminance for the surround conditions resulted from the reflected light of the surround lightings. In each condition, the reference stimuli with a lower luminance than the transmitted surround lightings were presented in the experiment, but these data were excluded from the analysis (Table 2). The lowest luminance in a transparent display was the luminance of the transmitted surround lightings. Even if the participants perceived that the reference stimulus was darker than the test stimulus, they were not able to physically adjust the brightness of the test stimulus below the luminance of the transmitted lightings.

Table 2. Measured Luminance of the Reference Stimulus for All Surround Conditions

Gray value of reference stimulus	Ambient 1[a]		Ambient 2			Ambient 3			Ambient 4		
	5500 K	6500 K	5500 K	6500 K	13000 K[b]	5500 K	6500 K	13000 K	5500 K	6500 K	13000 K
70									48.1	47.7	47.9
80						65.8	65.4	65.3	63.4	63.0	63.2
90					83.8	83.5	83.2	83.1	81.2	80.8	81.0
100			105.5	105.3	104.1	103.9	103.5	103.4	101.5	101.1	101.3
120	156.9	156.7	153.9	153.8	152.6	152.3	152.0	151.9	150.0	149.6	149.8
140	216.2	216.1	213.2	213.0	211.8	211.5	211.2	211.1	209.2	208.8	209.0
160	286.5	286.3	283.5	283.3	282.1	281.8	281.5	281.4	279.5	279.1	279.3
180	368.1	368.0	365.1	365.0	363.8	363.5	363.2	363.1	361.2	360.8	361.0
200	461.5	461.3	458.5	458.3	457.1	456.9	456.5	456.4	454.5	454.1	454.3

[a] In ambient 1 condition, 13000 K was excluded. / [b] Lower by 50 cd/m^2 compared with the other CCTs.

In the experiment, the fixation point was presented within 500 ms, and then the reference and test stimuli were presented simultaneously. The reference stimulus was presented from the fifteen levels at random. When participants pressed the up-arrow or down-arrow keys to match the brightness of the two stimuli, the gray value of the test stimulus changed in increments or decrements of two values. The method of adjustment had a drawback that participants' responses were influenced by the direction of change. To counterbalance this bias, the starting luminance of the test patch was randomized: one was below the luminance of a reference patch and the other one above that. After the response of one trial, the next stimulus was shown. The experiment consisted of eleven sessions (4 surround luminance × 3

CCTs). The bright condition for 13000 K was excluded. The order of the CCT was randomized. There were 30 trials per session totaling 330 trials (15 levels of brightness of a reference stimulus × 2 starting points of a test stimulus × 11 sessions). The condition of surround luminance started from the brightest condition and ended with the darkest condition. This was designed to provide sufficient time for the participants to adapt to the surround luminance levels and CCTs. The transparent display unit used in this experiment was a prototype built by Samsung display for R&D purpose. It had transmittance of about 30%. Informed consent was obtained from all subjects prior to participation in the study.

2.2 Result

A Total of 32 subjects participated in Experiment 1 (12: 5500 K, 8: 6500 K, and 13: 13000 K). The data of one subject in ambient 1 and 6500 K condition was excluded because the subject felt eye fatigue and wanted to stop the session. The subject started the experiment from ambient 2 condition on the next day. To analyze the effect of CCT on the transparent effect, we performed an Analysis of Variance (ANOVA) using Minitab 16. Because the excluded data were different according to the illuminance of surround lightings, we analyzed each illuminance condition separately. In ambient 2 condition, the condition of 13000 K was excluded because the amounts of transmitted light were different from the other two conditions. The main effects of CCT were not significant (Ambient 1: $F(1,175) = 0.99$, $p = 0.320$; Ambient 2: $F(1,216) = 0.61$, $p = 0.436$; Ambient 3: $F(2,496) = 1.03$, $p = 0.358$; and Ambient 4: $F(2,549) = 0.22$, $p = 0.803$).

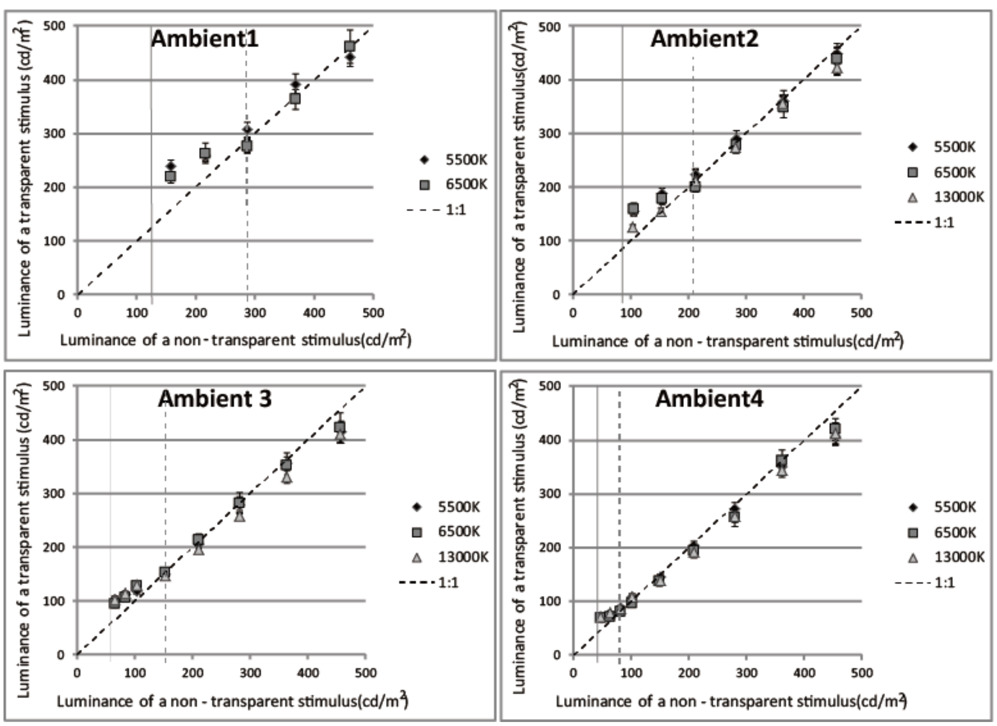

Fig. 2. Luminance of the transparent test stimuli that the participant matched with the brightness of the non-transparent reference stimuli.

Figure 2 shows the results for each surround luminance condition. The gray solid lines represent the transmitted light through the transparent display. The gray dashed lines correspond to the points at which the luminances of the reference and test stimuli were the same when the participants perceived two stimuli with the same brightness. The distance

Optics EXPRESS

between the gray solid and black dashed lines for each condition is in the range of the transparent effect.

Table 3. Average Luminance of Test Stimulus in All Surrounding Conditions

Luminance of reference stimulus (cd/m^2)	Average luminance of a test stimulus (transmitted light + self-luminous light on screen)										
	Ambient 1[a]		Ambient 2			Ambient 3			Ambient 4		
	5500 K	6500 K	5500 K	6500 K	13000 K[b]	5500 K	6500 K	13000 K	5500 K	6500 K	13000 K
48.14									**69.4**	**69.1**	**71.1**
65.76						**102.5**	**95.1**	**103.0**	**70.7**	**70.3**	**78.5**
83.54					**122.1**	**112.2**	**105.9**	**113.7**	87.9	81.2	87.0
105.49			**154.3**	**159.7**	**125.2**	**118.1**	**127.3**	**129.0**	107.9	97.3	108.8
156.95	**239.4**	**218.5**	**187.7**	**177.6**	155.9	149.4	152.3	147.8	146.2	137.8	139.6
216.52	**258.9**	**262.8**	223.2	200.5	211.2	206.2	214.3	196.1	204.2	193.2	191.6
286.45	307.2	276.7	290.2	278.1	274.0	278.8	282.2	259.0	271.6	256.7	258.5
368.14	390.3	363.2	360.8	348.5	356.7	355.3	351.6	330.5	349.4	361.7	344.9
461.49	442.4	460.7	448.5	437.8	421.7	414.4	422.4	410.7	406.9	420.4	412.1

[a] In the Ambient 1 condition, 13000 K was excluded. / [b] Lower by 50 cd/m^2 compared with the other CCTs.

In the results, the transparent effect only appeared within a certain range. Within that range, the participants judged that a brighter test stimulus had a similar brightness to a reference stimulus. The range changed according to the surround luminance. Namely, the transparent effect correlated with the amount of transmitted light. Table 3 shows the luminance of a reference stimulus and the average luminance of a test stimulus when the participants matched the same brightness of two stimuli. The average luminance of a test stimulus was the sum of the luminance of the transmitted lights and that of the self-luminous light. Although the luminance of a reference stimulus was measured a little differently in each condition (Table 1), the brightest luminance among the reference stimuli is given in Table 3. The bold type represents the range of the transparent effect. As the amount of transmitted light decreased, the range of the transparent effect decreased. The transparent effect disappeared when the non-transparent stimuli had within 200–250% luminance of the transmitted light through the transparent display.

To validate the effect of the amount of transmitted light, we performed a multiple-regression analysis. The predictors were the amount of transmitted light and luminance of a non-transparent reference stimulus. CCT was excluded because it was not significant in the previous analysis. The analysis results indicate that the two predictors were significant (the amount of transmitted light: $t = 10.48$, $p < 0.001$; luminance of reference stimulus: $t = 81.20$, $p < 0.001$). The luminance of a transparent test stimulus was predicted by Eq. (2), which was also significant (adjust $r^2 = 81.9\%$, $p < 0.001$).

$$Y_{transparent} = 0.690 + 0.844 \times Y_{non-transparent} + 0.544 \times T \cdot Y_{lightings} \tag{2}$$

Here, T is the transmittance of a transparent display, $Y_{lighings}$ is the luminance of the transmitted surround lightings, $Y_{non\text{-}transparent}$ is the luminance of a non-transparent stimulus, and $Y_{transparent}$ is the predicted luminance of a transparent stimulus that had a similar brightness to the non-transparent stimulus.

2.3 Similarity between the transparent effect and perception of transparency

The transparent effect has been mentioned in several studies regarding the lightness perception of transparency [12–15] and media [11], though it has not been defined by a specific name. The results of these studies provide evidence for explaining the brightness perception in a transparent display.

A detailed mechanism has not yet been revealed, but most researchers agree that transparency affects brightness perception. Some researchers have proposed that the underlying mechanisms of perceiving reflected light (or color) and perceiving transparency are similar [13–15]. We do not perceive yellow color when a red object is reflected on a green object. This phenomenon is explained by the layer concept. The image entering the retina is divided into two different layers: the image of a red object and that of a green object; so, we can distinguish two different colors, and do not perceive a mixed color. In a similar way, the brain can separate the brightness of illumination and lightness of a transparent surface according to the layer concept.

Applying this concept to our result, the participants seemed to separate the transmitted light from the illumination and self-luminous light from the screen in the range of the transparent effect. The participants did not judge the brightness of a test and reference patch on the basis of absolute luminance, which may be an example of the layer concept.

3. Proposed optimal gamma correction based on gray scale perception in a transparent OLED display

3.1 Proposed 2-gamma correction based on transparent effect

According to the transparent effect, the brightness perception had two trends for the transparent OLED display. The first trend showed that a transparent stimulus was perceived brighter than a non-transparent one under 250% luminance of the transmitted light through the transparent display. The second trend showed that a transparent stimulus had the same brightness as a non-transparent one. Therefore, we concluded that the range of the first trend required a gamma adjustment to improve the image quality, but the second trend had a similar gamma to the most preferred display gamma of a non-transparent display.

On the basis of these results, we proposed a “2-gamma correction” which has two different gamma values for the transparent OLED display. Within the range of the transparent effect, the adjusted gamma value can be applied to improve the visibility of low-tones. In previous research [9], the lower monitor gamma was preferred as the transmittance or the surround luminance increased. As the display gamma decreased, the L* value increased when the gray value increased by 1. In particular, the change was noticeable in the low-tones, so that the low-tones of the images on the transparent display became more visible. For more than 250% luminance of the transmitted light, the transparent effect did not appear; so, we used the 2.2 monitor gamma, which is known as the optimal gamma in a normal display.

Figure 3 shows the CIELAB L* value comparison between the 2.2 and 2-gamma corrections on the transparent display. We calculated the lightness in the overall tone-range when the surround light changed from the dark condition to Ambient 4 condition. The L* distribution of the 2.2 gamma changed from the black dashed-line to the black solid line in the transparent OLED display. The 2-gamma correction had an adjusted gamma value of 1.7 gamma in the low-tones. The adjusted gamma value was determined in previous research [9]. On the other hand, the 2-gamma correction followed the shape of the 2.2 gamma in the high-tones.

Optics EXPRESS

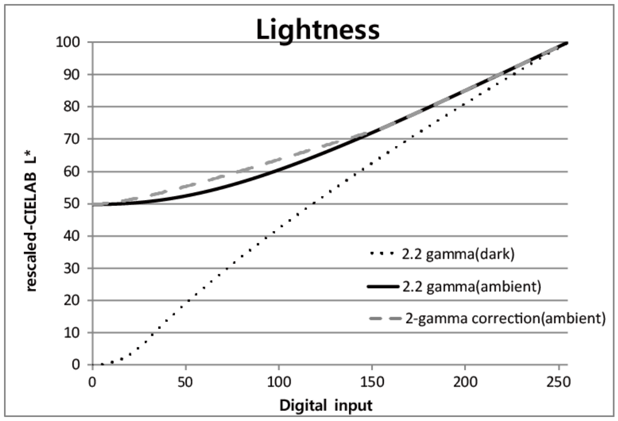

Fig. 3. Lightness curves of various display gamma in the transparent display.

3.2 Experiment 2: verifying the 2-gamma correction for a transparent OLED display

To verify the 2-gamma correction based on the transparent effect, we conducted a preference experiment. There were two independent variables: the gamma types and surround conditions. The two gamma types were the 2-gamma correction and the original 2.2 gamma. The 2-gamma correction had a 1.7 gamma value in the range of the transparent effect and a 2.2 gamma value in the other range. The original 2.2 gamma was used as the control level. The surround conditions had two levels: the dark and ambient conditions. Ambient 1 condition was used in Experiment 1 (450 cd/m^2, 6500 K). We set the brightest ambient condition by considering the usage of a transparent display for Public information Display (PID) [16] in the outdoor environment and the standard for viewing wearable content [17].

Twelve images were used as the test images: four images for public information display and eight natural images including skins, skies, and grasses. Each image was adjusted by the 2-gamma correction. A total of 24 images (including the original 2.2 gamma) were presented on our transparent display. The visual angle size of the images was 44 × 26. The order of images was randomized.

The participants were asked to rate the preference of images (1: not preferred, 4: neutral, 7: very preferred). The experiment commenced under the dark condition and the original test images were presented without transmitted lights. The next was the ambient condition. Before starting each session, an adaptation time of 5 minutes was provided for each illumination. We used the same transparent display in the experiment 1.

We performed an ANOVA on the data of eighteen participants using Minitab 16. The main effects of the gamma types and surround condition were not significant (gamma types: $F(1, 843) = 0.39$, $p = 0.534$; surround conditions: $F(1, 843) = 0.15$, $p = 0.697$). The interaction between the types of gamma and surround condition was significant ($F(1, 843) = 18.30$, $p < 0.001$). Under the dark condition, the images with the reference 2.2 gamma value were preferred. On the other hand, the 2-gamma correction was preferred under the ambient surround condition in Fig. 4.

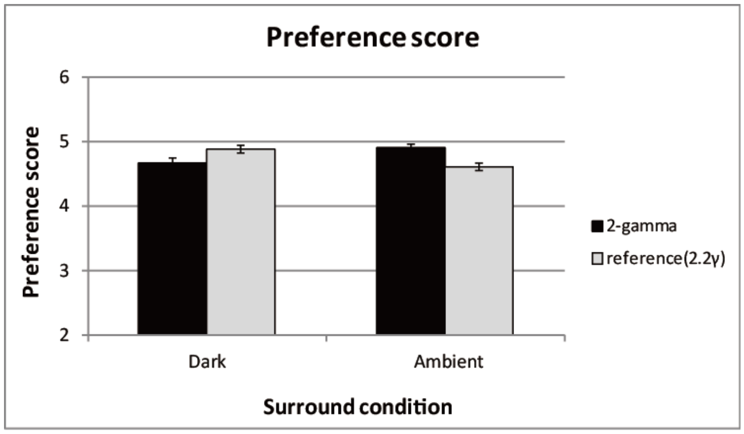

Fig. 4. Preference scores of reference and 2-gamma correction.

The trends of the preference scores were slightly different according to the image types in Fig. 5. In the case of the images for PID, participants preferred images with 2-gamma correction under the ambient surround condition. We performed ANOVA on the data of four PID images. The main effect of gamma types was significant ($F(1, 267) = 4.60$, $p < 0.05$), but the main effect of surround condition was not significant ($F(1, 267) = 0.95$, $p = 0.330$). The interaction between the types of gamma and surround condition was significant ($F(1, 267) = 11.88$, $p < 0.01$). Under the ambient surround condition, the 2-gamma correction was more preferred than the original 2.2 gamma. When the information in the images was important, images with gamma correction obtained a higher preference than the reference 2.2 gamma. This implied that increasing lightness of the low gray parts affected the legibility.

In the case of the natural images, the preference scores for the 2-gamma correction were similar to the reference under the ambient surround condition. From the results of the ANOVA, the main effects of the gamma types and surround condition were not significant (gamma types: $F(1, 557) = 0.71$, $p = 0.401$; surround conditions: $F(1, 557) = 0.06$, $p = 0.805$). The interaction between the types of gamma and surround condition was significant ($F(1, 557) = 7.93$, $p < 0.01$). Although the lightness of the low gray parts increased, the perceived image quality remained similar overall.

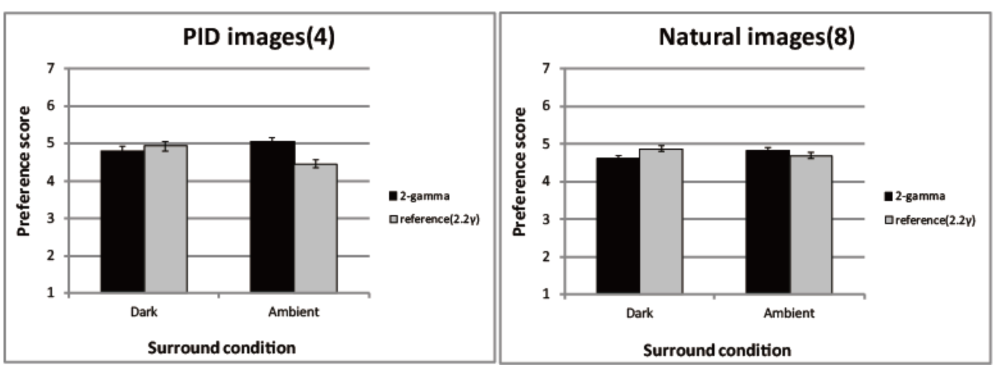

Fig. 5. Preference scores of the PID and natural images.

4. Conclusion

We conducted an experiment on the gray scale perception of a transparent OLED display. Within a certain range, the participants perceived the transparent patch as darker than the non-transparent one even when the two had a similar luminance transparent stimulus, which we called the transparency effect in our previous study [10]. The range of the transparent effect

Optics EXPRESS

was 200–250% luminance of the transmitted light through the transparent display. We confirmed that the transparent effect also appeared in the gray scale perception as well as in the black perception of the transparent display.

To demonstrate the significance of this result in practical applications, we proposed a new tone-curve based on the transparent effect and conducted a simple experiment to demonstrate the validity of this curve. The participants preferred the new tone-curve, especially for PID images, which can be a further evidence in support of the transparent effect. Moreover, the results implied that the range of the transparent effect was valid.

However, the results obtained in this study are not sufficient to completely explain the transparent effect. We will need to firmly establish the definition of the transparent effect by integrating the studies on perceiving transparency and lightness perception through media (including a transparent display). It is also necessary to determine the precise range of the transparent effect for each situation and to develop it into a generalized theory in a further study.

Nevertheless, this study is the first to quantify the effect of the medium on gray scale perception through transparent OLED displays and to demonstrate its potential for practical application. This research will provide a foundation for future research in the field of influence of the medium on human perception.